Feasibility of Powerline Communications (PLC) on Future Spacecraft

EMI/EMC Test Results on COTS PLC Technology

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***Abstract* — Cable harnessing mass continues to be a problem for spacecraft development, particularly with increasingly complex payloads and constraints to their mass and costs. As a strategic initiative to reduce cable harnessing on flight missions, NASA JPL's Powerline Communications (PLC) research and technology development (R&TD) effort investigates the ability to combine power and data onto the same cable conductors. Research and development of PLC technology, including testing of commercial off-the-shelf (COTS) modules and design of custom PLC unit, aim to articulate the opportunity to infuse this technology into NASA flight projects. This paper illustrates the feasibility of Powerline Communications on future spacecraft through Electromagnetic Interference/Compatibility (EMI/EMC) testing on COTS PLC components including conducted emissions and susceptibility as well as radiated emissions and susceptibility.**

Keywords—powerline communications, electromagnetic compatibility, electromagnetic interference, smart cabling, cable harnessing, technology infusion, research and development, mass reduction

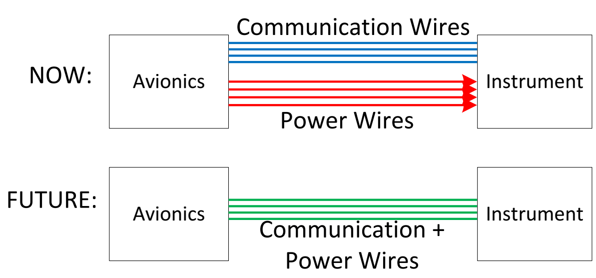

Figure 1: Comparison Between Traditional Harnessing and Powerline Communications

I. Introduction

When formulating a spaceflight mission, significant constraints are spacecraft mass and volume, which drive project cost. Roughly costing one million US dollars per kilogram for missions to the moon and beyond, it is imperative to optimize spacecraft designs so that missions can be launched at lower costs or with additional payload capabilities. Powerline Communications (PLC) can address this challenge by reducing cable harnessing mass, potentially eliminating signal harnessing entirely for some spacecraft subsystems. For example, one NASA JPL project that could have benefitted greatly from PLC is NuSTAR, the Nuclear Spectroscopic Telescope Array. If its mast harness utilized PLC, it could have saved 1.36 kg of conductor mass. This mass could have been allocated to additional payloads, including mast dynamics characterization hardware that was de-scoped due to mass constraints.

Combining Power and Data Using Powerline Communications is a NASA JPL research and technology development (R&TD) effort to smartly reduce cable harnessing mass for future spacecraft. The PLC research team aims to demonstrate the technology's performance using COTS products and later deliver an in-house system that can be infused into future flight projects in its three-year project cycle (FY16-18). This R&TD initiative acknowledges the multiple research efforts made on PLC, especially previous work done by F. Grassi, S. A. Pignari, and J. Wolf, whose efforts helped guide this paper significantly.

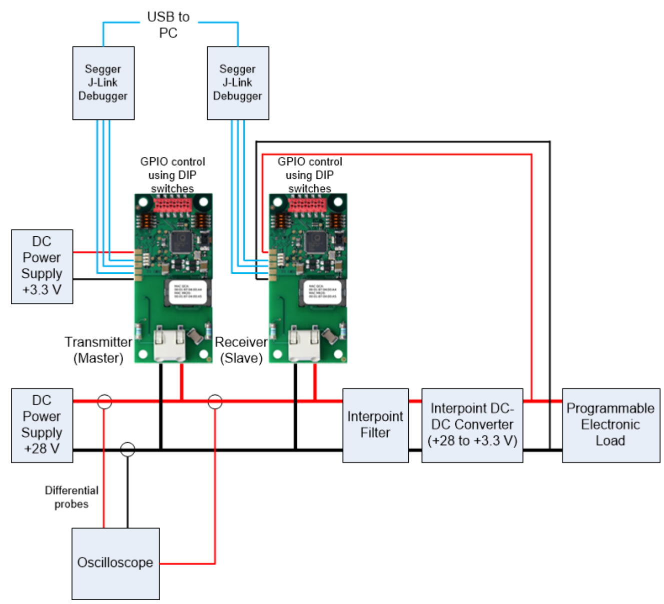

Figure 2: PLC Testbed Configuration

Although powerline communication is a reliable, mature technology currently used for home and automotive applications, the Electromagnetic Compatibility (EMC) of PLC is crucial to verify its utility for spaceflight. It has been a NASA JPL best practice to isolate power and communication harnessing as much as possible to prevent electromagnetic interference (EMI) especially radiated emissions between spacecraft power and subsystem signaling. Thus, determining the technology's capability and tailoring it for stringent spaceflight requirements are milestones the project hopes to achieve with support from JPL's EMC Group. After establishing a PLC testbed and successful powerline communication between two COTS modules, two rounds of EMI/EMC testing have been performed. The first set focused on preliminary conducted emissions (CE) and susceptibility (CS). Using data from this first test, testbed modifications were made in preparation for the second test set, which focused on radiated emissions (RE) and susceptibility (RS) while revisiting CE with expected improvements.

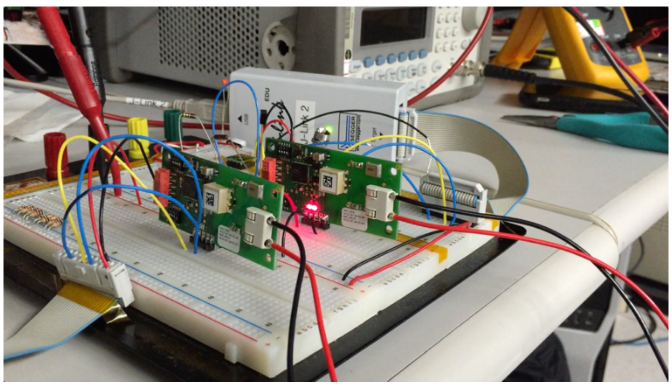

Figure 3: PLC Modules Operating in DC Power Bus

II. Implementation

Powerline communications allow signal transmission to be shared on the power harnessing conductors. For example, Figure 1 illustrates an example of PLC used for control and telemetry between spacecraft avionics and instrument payloads. This transmission is done through the coupling of high frequency communication signals onto the power bus. PLC modules either encode and/or decode these signals depending on their designated purpose.

PLC is a robust technology, for it has numerous commercial applications, including the automotive, industrial, and "smart home" sectors. These applications involve low-frequency, high voltage AC powerlines. Given PLC's capability to perform under these conditions over long distances, leveraging the technology to operate on comparatively lower voltage DC spacecraft power buses would be an attainable stepping stone [1].

For this project, PLC for DC differential buses was demonstrated with the I2SE Stamp 1 module, which features a Qualcomm QCA 7000 PLC processor. With low power requirements, 3.3 Vdc input voltage with 0.5 W power consumption, the Stamp 1s performed reliably with adjustable data rates up to 10 Mbps. The QCA 7000 transmitted and processed data signals using orthogonal frequency division multiplexing (OFDM). Bit error rate (BER) was validated through receiver error check printouts using SEGGER J-Link debuggers that linked with the Stamp 1s through SWD protocol.

The testbed transitioned to a more spacecraft-like setup with a 28 Vdc twisted wire pair (TWP) power harness linking the transceiver inputs of the Stamp 1 modules. Similar to Grassi's PLC prototype's configuration, an EMI filter and DC-DC converter were coupled, respectively in that order, from the TWP to a programmable load [1]. Unlike their setup, however, the transmitter (TX) module was powered by its own 3.3 Vdc power supply, whereas the receiver (RX) module was powered from the DC-DC converter's 3.3 Vdc output secondary. A computer monitored data transmission through the SEGGER debuggers and oscilloscope captured time-domain voltage on active and return lines as well as current on the active line.

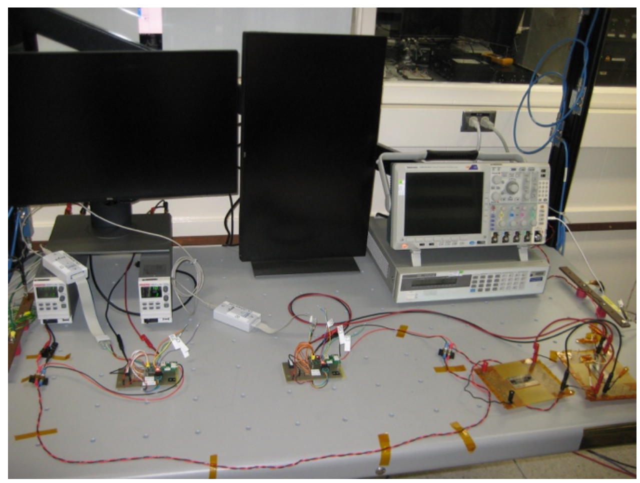

Figure 4: Initial PLC EMC Testbed Configuration

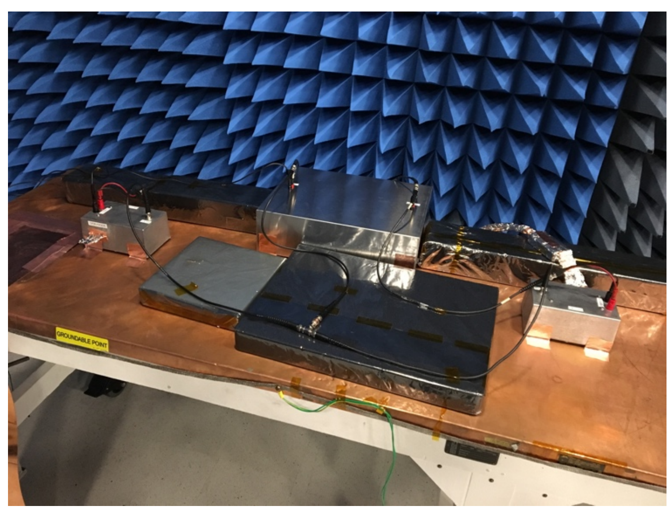

Figure 5: Modified PLC EMC Testbed Configuration

III. Test Methodology

At JPL, EMI/EMC requirements are based off the US Military Standard, MIL-STD-461. The first set of CE and CS tests were performed in accordance to MIL-STD-461C, but the second test set, RE, RS, and CE, were done in accordance to MIL-STD-461F, a more up-to-date requirement. Note that these tests are nominally performed on the input powerlines of the equipment under test (EUT), but in the interest of PLC the spacecraft power bus, 28 Vdc in this case, was selected as the designated test article. By specifically characterizing and stressing this powerline, the PLC modules' transceiver performance and overall robustness will be thoroughly investigated.

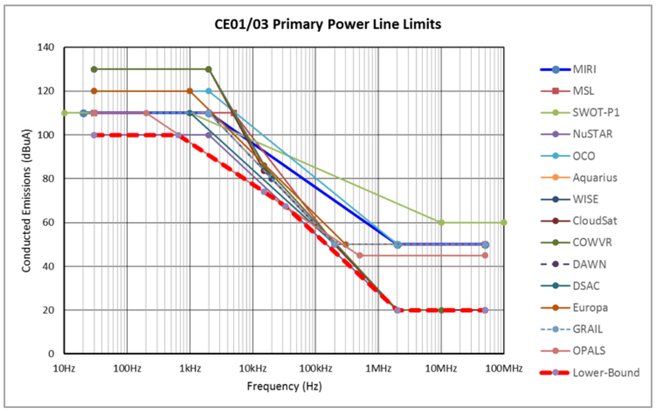

Figure 6: Survey of JPL Conducted Emissions Requirements

A. *Conducted Emisisons (CE101/102)*

CE101 and CE102 characterize the current ripple of the test article's primary power bus from a spectrum of 30 Hz to 50 MHz. In addition to MIL-STD-461F's limit line, a survey of fourteen NASA JPL flight projects' CE101/102 limits was generated to produce requirements for the PLC project. As shown in Figure 6, the lower-bound limit was used for PLC's preliminary CE101/102 success criteria. For time domain CE measurements, acceptable noise differential between active and return lines should not exceed 2.8 Vpp [3].

Per MIL-STD-461, the input powerlines of the test article are measured; for PLC, however, the 28 Vdc powerline where the Stamp 1 transceiver modules communicate, is tested. Both common (CM) and 2-wire differential mode (DM) currents are measured to illustrate a complete picture of the article's current ripple profile. Various current probes measured the current ripple, which is recorded onto a spectrum analyzer. Preliminary CE101/102 testing was performed on TWP whereas the second test used shielded BNC coaxial harnessing.

Additionally, time domain CE data was collected through the measurement of active and return line voltages (relative to facility ground) and active line current. The difference between active and return line voltages yielded time domain noise. For all tests, the Stamp 1 TX module was set to maximum data rate, 10 Mbps, to create a nosiest test configuration. The RX module was set to receive, with BER assessed through the SEGGER debugger.

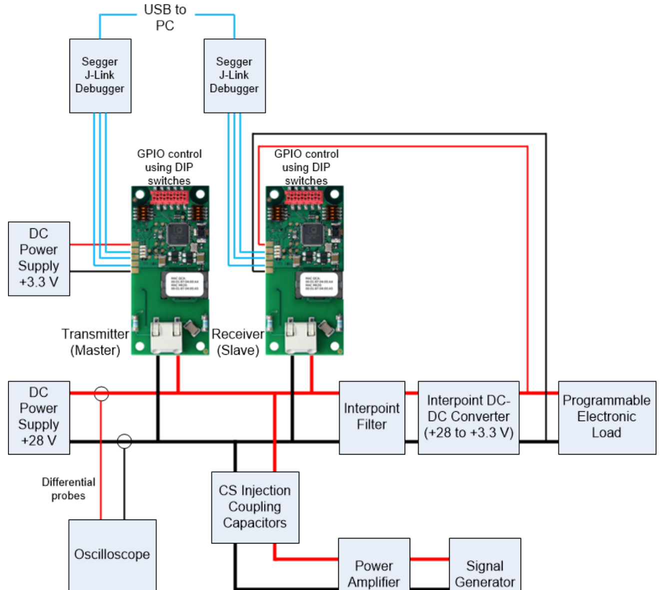

Figure 7: CS02 Test Configuration

B. *Conducted Susceptibility (CS01/02/06)*

These three tests subject the test article, the 28 Vdc powerline, with AC and transient waveforms and assess it for immunity and/or susceptibility. Based off of MIL-STD-461C, CS01/02 together provide an AC sweep of 1 Vrms from 30 Hz to 50 MHz whereas CS06 couples bursts of transients two times the power bus voltage, positive and negative. These ± 56 Vpp transients, 10 µs in period, pulsed at 60 pps for 5 minutes, respectively [3].

For CS01/02, the AC signal was signal was produced by a signal generator and power amplifier, which was injected inductively and capacitively for CS01 and CS02, respectively. Inductive coupling via an injection probe provided a differential signal whereas capacitive coupling was done in parallel to each line, yielding a common mode signal. CS06 followed the same capacitive coupling as CS02, but with a pulse generator as the transient source. Performed manually, the injected signals were measured differentially using an oscilloscope. For all three conducted susceptibility tests, the PLC modules would have to perform with zero BER to succeed.

C. *Radiated Emissions (RE102)*

RE102 measures the electric fields radiated 1 meter away from the test article spanning 10 kHz to 18 GHz. Per MIL-STD-461F, various antennas are used, with both horizontally and vertically polarized fields recorded starting at 30 MHz [2]. Depending on the configuration, preamplifiers are used to improve the sensitivity of the receiver antenna. Traditionally, RE102 is a stringent test that requires effective design, fabrication, and assembly to meet requirements. If these are done inadequately, spacecraft subsystems and payloads are subject to crosstalk and other interference that can pose tremendous risk to their respective projects and missions.

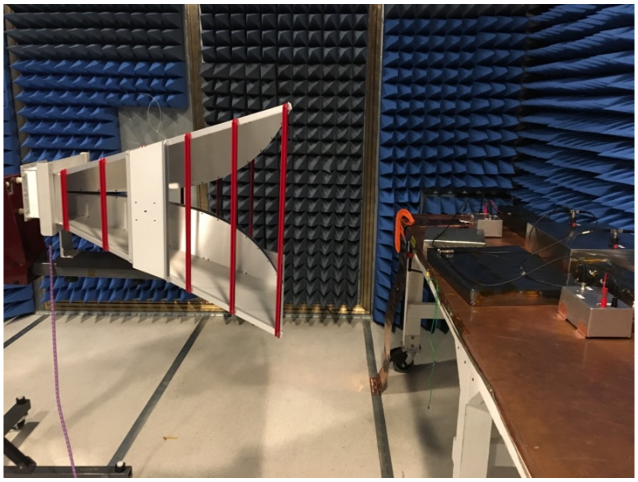

Figure 8: RE102 Test Configuration, Vertical Polarization 200 MHz to 1 GHz

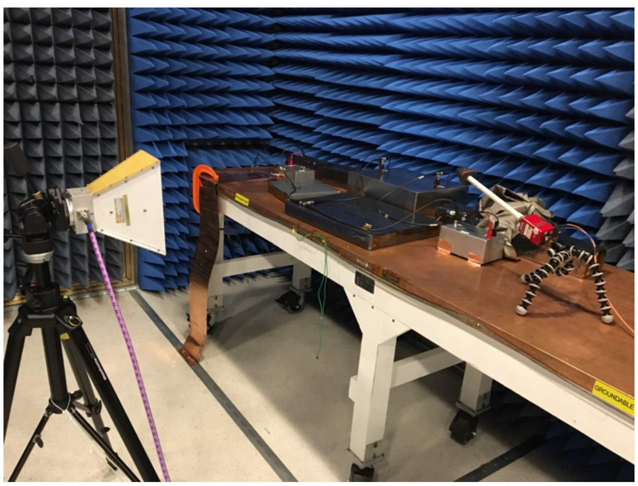

Figure 9: RS103 Test Configuration, Horizontal Polarization 1 GHz to 18 GHz

D. *Radiated Susceptibility (RS103)*

As a counterpart to RE102, RS103 exposes the article to RF electric fields from 2 MHz to 18 GHz. For MIL-STD-461F, spacecraft test articles are subjected to 20 V/m throughout the whole frequency range. This electric field is pulse modulated at 1 kHz with a 50% duty cycle [2]. Similar to RE102, various antennas and amplifiers are used; both horizontally and vertically polarized electric fields are generated starting at 30 MHz.

Note that unlike Figure 4, the RE and RS tests were performed in an anechoic chamber with the test articles housed in aluminum chassis and shielded coaxial harnesses. These testbed modifications were made not only in preparation for RE and RS, but in response to preliminary CE data. Similar to the CS tests, the PLC modules would have to perform with zero BER to succeed.

IV. Test Results

A. *Conducted Emissions (CE01/03)*

1) First Set

With a stringent frequency domain limit, both common and differential mode measurements exceeded the CE limit line. The DM mode plot in Figure 10 shows high exceedances at the 1-30 MHz band. This is atrributed to the orthogonal frequency division multiplexing (OFDM) protocol of the Stamp 1 modules. For this product, this communication continues even without user data transmitted, thus acting like a handshaking signal between PLC modules.

Time domain measurements of the current ripple noise affirmed the CE01/03 frequency domain plots. With an average of 6.69 Vpp, the noise between PLC active and return lines more than exceeds the nominal JPL standard of 2.8 Vpp noise. This limit is necessary to mitigate interference between multiple subsystems that share the same power harnessing. Thus, PLC using the Stamp 1 modules failed the first set of CE testing.

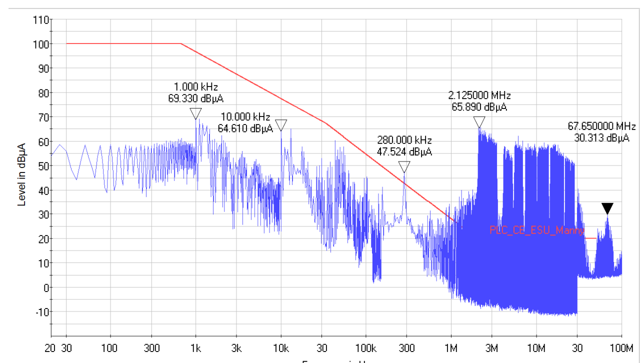

Figure 10: CE101/102, Differential Mode (First Set)

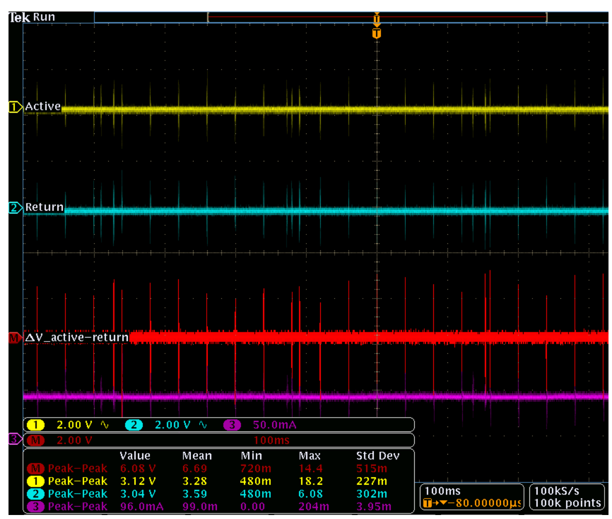

Figure 11: Time Domain Conducted Emissions, 6.69 Vpp Average (First Set)

The PLC modules' signals were attenuated using a capactive filter. 90 µF parallel from active and return transceiver input lines along with 1 µF in series of each line (intended to isolate the PLC modules from the powerline) reduced the conducted emissions to an average 1.4 Vpp. This modification was installed into the testbed along with shielding the modules within chassis before RE, RS, and the second CE test set.

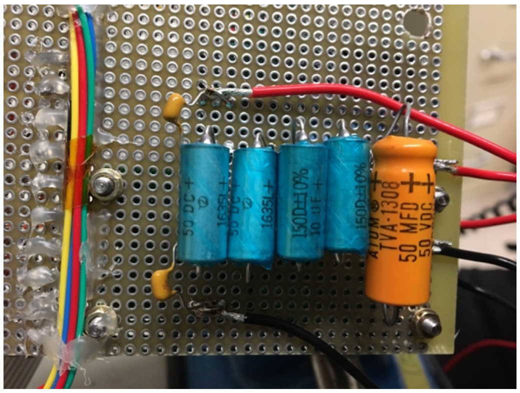

Figure 12: 90 µF Filter with 1 µF Isolation Capacitors

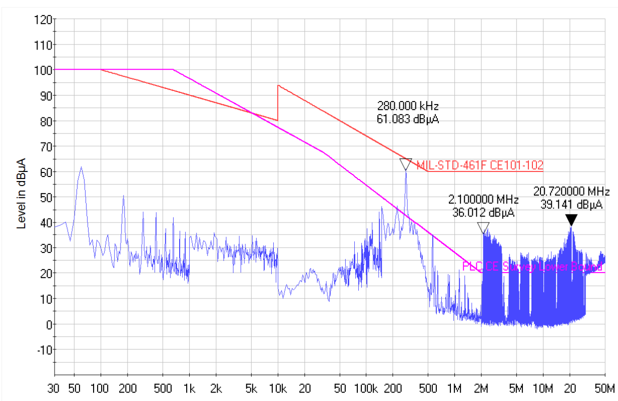

Figure 14: CE101/102, Differential Mode (Second Set)

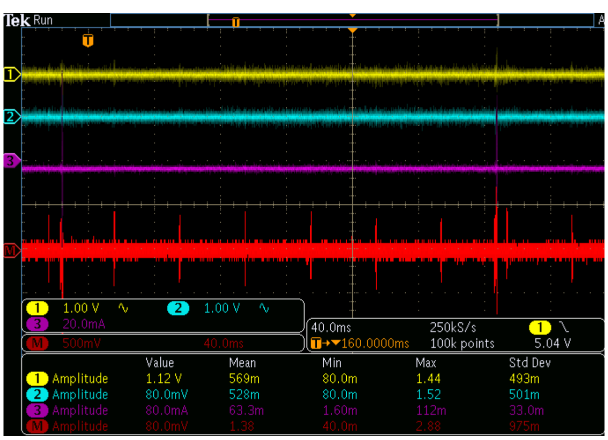

Figure 13: Attenuated Time Domain Conducted Emissions

2) Second Set

The capacitive filter modification worked very well in the frequency domain. CE101/102 plots only exceeded the JPL CE survey (the highest being 61 dBµA at 280 kHz), but not the MIL-STD-461F limit for 28 Vdc test articles.

B. Conducted Susceptibility (CS01/02/06)

Despite a constant level of 1 Vrms (2.8 Vpp) AC ripple, the PLC system performed reliably with zero BER from 30 Hz to 50 MHz. Similarly, CS06 injection transients yielded no susceptibility to the PLC modules. This robustness can be attributed to the OFDM scheme of the modules, for by design, if one carrier frequency is subject to interference, there are many more frequencies that can be immune and capable to transmit. Similar to CE, retesting CS should be done to determine the immunity threshold of these devices.

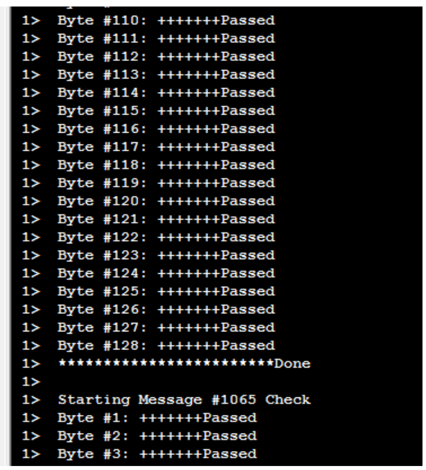

Figure 15: Conducted Susceptibility BER Check

C. Radiated Emissions (RE102)

Although efforts were made to use shielded cables and chassis to house the PLC testbed components, PLC radiated high electric fields that greatly exceeded MIL-STD-461F limits. These include frequencies seen at CE101/102 (e.g. 280 kHz and 27.97 MHz) and beyond. Even with RF fabric draping over the PLC EMC testbed, the attenuated RE signals still well surpassed the limit.

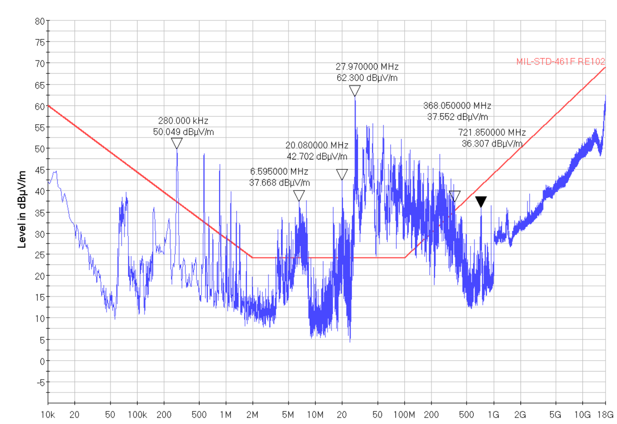

Figure 16: RE102, Vertical Polarization

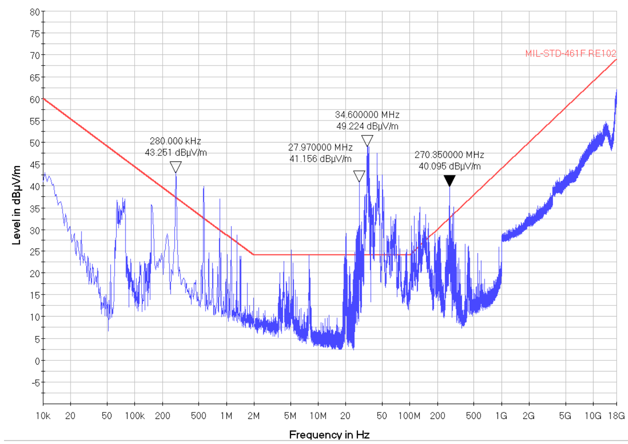

Figure 17: RE102 with RF Cloth Shield, Vertical Polarization

The radiated emissions issue was expected to pose a challenge for this technology. When designing an in-house PLC system, attention to signal integrity must be made to mitigate potential RE. Since PLC aims to reduce harnessing mass, more shielding can be added to protect other subsystems from PLC radiated emissions as well as protect the powerline from RS.

D. Radiated Susceptibility (RS103)

Throughout its frequency spectrum, 20 V/m pulse modulated electric fields did not subject the PLC system to any susceptibilities. The braided shielding of the coaxial cables and various chassis provided sufficient protection for the PLC modules. With this test article configuration, it would be worth investigating what radiated electric field levels and modulations would cause EMI or perhaps destruction to the PLC modules.

V. CONCLUSION

Given the data from these tests, more needs to be done to determine the feasibility of Powerline Communications on future spacecraft. Commercial parts have proven useful for demonstrating the functionality of the technology in spacecraft-like configurations. The first two sets of EMI/EMC testing were effective characterizations of the technology and pathfinders on the way to custom design of a spacecraft-focused PLC system.

Although both conducted and radiated emissions exceeded their respective limits, better design and assembly of PLC hardware can reduce emissions significantly. The capacitive filter to the PLC transceiver inputs confirms this for CE101/102. For RE noise, attention must be drawn to PLC signal integrity and appropriate shielding of harnesses, including using shielded twisted wire pairs. It must also be noted that the Stamp 1 PLC module was built for high voltage, long distance AC environments; designing the transceivers to output signals to lesser amplitudes would help. This can be contrasted to harnessing required for SmallSats and CubeSats, which are much shorter in length than most spacecraft let alone PLC's current terrestrial applications.

Conducted and radiated susceptibility tests have been a cause for optimism, for these commercial units proved to be quite robust to MIL-STD-461C/F requirements, respectively. However, work should be done to "test to break" and determine the immunity threshold for these devices.

VI. ACKNOWLEDGEMENTS

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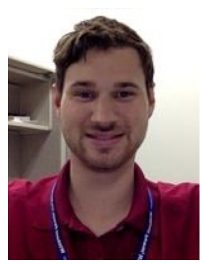
BIOGRAPHIES

Manuel Martin Soriano is an EMC Engineer at NASA Jet Propulsion Laboratory. He is co-lead EMC engineer for JPL payloads in development for the International Space Station: Cold Atom Laboratory (CAL), ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), and Orbiting Carbon Observatory 3 (OCO-3). Additionally, he conducts EMI/EMC research on Powerline and Wi-Fi communication initiatives. Before joining JPL, he graduated from the University of Southern California with a BS in Electrical Engineering in 2016.



Andrew W. Mitchell is a Power Systems Engineer at NASA Jet Propulsion Laboratory since 2015. He is the Principal Investigator for the Powerline Communications R&TD task at JPL and also a contributor to the design efforts of multiple developing flight programs on Lab as well as a member of the MSL Curiosity Rover's surface engineering operations team. Prior to his work at JPL Andrew worked for Moon Express where he contributed to the development of the Power and Avionics subsystem for a future autonomous lunar lander. Andrew graduated with a BSE in Aerospace Engineering at the University of Michigan – Ann Arbor in 2012.